Shallow Water Dynamics in the Arabian Gulf and Gulf of Oman

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LONG TERM GOALS

The development of a three-dimensional, high resolution nowcast/forecast system for the Arabian Gulf and Gulf of Oman which encompasses scales of 10 km or less when warranted, using the most advanced finite element (FE) coastal hydrodynamic models. The modeled dynamics are to include tidal and wind-driven flow, buoyancy forcing, surface heat flux, river inflow, and turbulent mixing processes.

OBJECTIVE

The primary objective is development of a circulation model for the Arabian Gulf and connecting waters that realistically predicts the complex, 3-D circulation and mixing patterns in the region over seasonal, tidal, sub-tidal, and storm event time scales. Dynamical processes to be considered include the three dominant external forcings in the region, a strong evaporative flux, seasonal wind forcing, and freshwater river discharge. Not only are realistic current fields sought but, the hope is to gain understanding of the role each forcing mechanism plays in the strongly thermohaline-driven circulation. A particular emphasis will be placed on the three-dimensional currents and transport of mass, salt and heat through the Strait of Hormuz. Another aim of this study is to demonstrate the utility of the finite element approach using state-of-the-art, physically advanced, 3-D numerical models.

APPROACH

In working toward a nowcast/forecast predictive capability in the Arabian Gulf, two circulation models are employed. The first model, the Dartmouth College QUODDY model, represents the most dynamically advanced FE model to date. QUODDY is a 3-D, fully nonlinear model that includes tidal, wind-driven, and baroclinic physics, incorporating advanced turbulence closure. This model is applied over seasonal and synoptic event time scales towards then development of a realistic circulation climatology and in the assessment of individual forcing contributions to the overall circulation. A second model, ADCIRC, is advancing to include a baroclinic component (development by Dr. Rick Luettich at UNC). This model is currently exercised operationally at NAVOCEANO as a nonlinear simulator of tidal and wind-driven circulation. ADCIRC is a more probable candidate for real-time predictions and subsequent transition to operations, in the context of Naval applications, though it has lagged QUODDY with regard to the inclusion of baroclinic dynamics. Both finite element models are designed with modular dynamics in which certain mechanisms, such as heat flux, wind forcing, stratification, tides, or river inflow can be independently included or excluded from model equations. This modularity is used to examine the contributions of each component to the overall circulation dynamics.

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14. ABSTRACT
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WORK COMPLETED

The number of degrees of freedom associated with 3D, baroclinic models dramatically increase over that of 2D applications forcing consideration of computational cost for a given application. One approach to this problem is to limit mesh size by using either smaller spatial extents or courser resolutions. Another approach is to expedite solution of the model equations through the use of parallel processing techniques. Finite element models are well-suited to parallelization due to their element-based computations. The Dartmouth College circulation model, QUODDY is now parallelized using Open-MP directives and executes on shared memory multi-processor machines or single multi-threaded processors of distributed memory machines. The Open-MP modifications are implemented within and tested for the latest release of QUODDY, version 5.1. Collaborations with the HPCMO PET program (Dr. Timothy Campbell) have made this effort a reality. Only 5% of the code remains exclusively serial; such sections are largely devoted to I/O operations and user-defined subroutines. The QUODDY model is also portable, having been tested on the SUN Enterprise 10,000, SGI Origin 2000, and the IBM-SP3. This parallelization effort represents a tremendous advance in modeling capability and will have drastic implications in terms of the number and resolution of experiments that will be realistically possible using this model.

The strong thermohaline-driven circulation in the Arabian Gulf provides a considerable test for model temperature and salinity transport algorithms. Evaporation is the primary driving force which places great importance on specification of the surface boundary condition. Presently surface temperatures are nudged back to initial climatological values and surface salinity is allowed to freely evolve. As shown in Figure 1, vertical profiles of temperature at the Strait of Hormuz compare favorably to observed values while salinity is clearly over-mixed throughout the water column. One solution may be to also nudge surface salinity to initial climatology. This approach has been implemented and testing is underway. Ultimately spatially variable evaporative fluxes will be required.

A data assimilation effort began with the application of the linear harmonic inverse model, TRUXTON, to the Arabian Gulf. Assimilated data includes shipboard ADCP data acquired from NAVOCEANO and International Hydrographic Office (IHO) tidal station data. Finer points regarding the application of TRUXTON were investigated in collaboration with Dr. Chris Naimie at Dartmouth College. For example, a successful inverse application depends on appropriate parameter specification for the inverse solution technique, interpretation of error measures, and evaluation of the inversion. Experiments investigating the sensitivity of minimum depth and frictional coefficient on the resulting inverse solution in the Arabian Gulf are complete.

RESULTS

The seasonal circulation climatology previously generated by the state-of-the-art QUODDY 3-D FE model for the Arabian Gulf is used to test parallelization of the QUODDY code. Mesh resolution over the domain is variable (17440 nodes, 33322 elements), approximately 3 km in depths less then 40 m and 6 km elsewhere out to the open ocean boundary at 200 m depth in the Gulf of Oman. The loop-by-loop parallelization initially implemented is now replaced by a single parallel region resulting in less reliance on OpenMP thread management. Full precision verification against serial code computations is complete for three HPC platforms: Sun Enterprise 10,000, the SGI Origin 2000 and the IBM SP3, in effect making the code portable as well. This effort has resulted in near linear speed-up of model computations with respect to the number of processors (Figure 2a). Speed-ups by factors of 5 on 8 processors to 11 on 32 processors on the Sun Enterprise 10,000 have been realized. The CPU time was decreased from 9 sec/timestep on a single processor to less than 2 sec/timestep using 32 processors. Ultimately a 10 day simulation that had taken approximately 22 hours on one CPU now runs in only 8 hours on 32 processors of the shared memory SUN E10000 supercomputer. Efficiency is improved for cases involving higher vertical resolution (increased numbers of vertical nodes) as shown in Figure 2b.

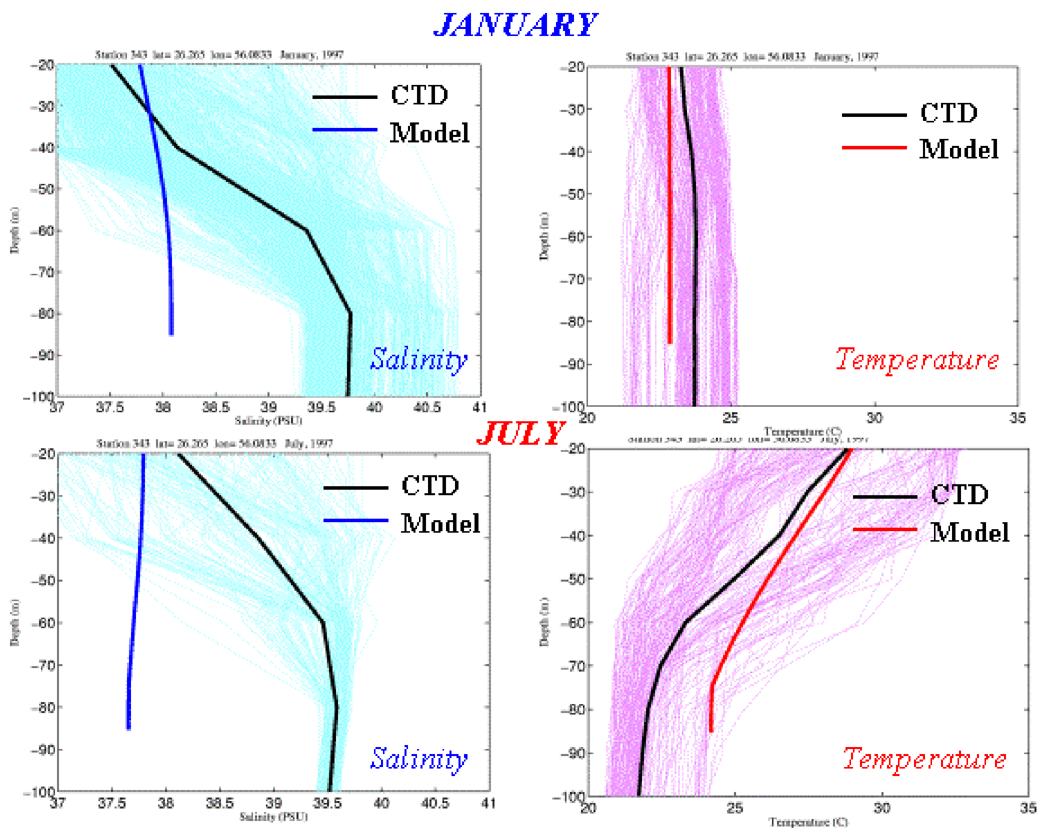

Figure 1. Model-data comparisons between vertical profiles of salinity (left) and temperature (right) in the Strait of Hormuz during Winter (top) and Summer (bottom). Surface temperatures are nudged to initial climatological values; surface salinity is unrestrained. QUODDY computed temperatures are reasonably reproduced while salinity values are clearly over-mixed throughout the water column.

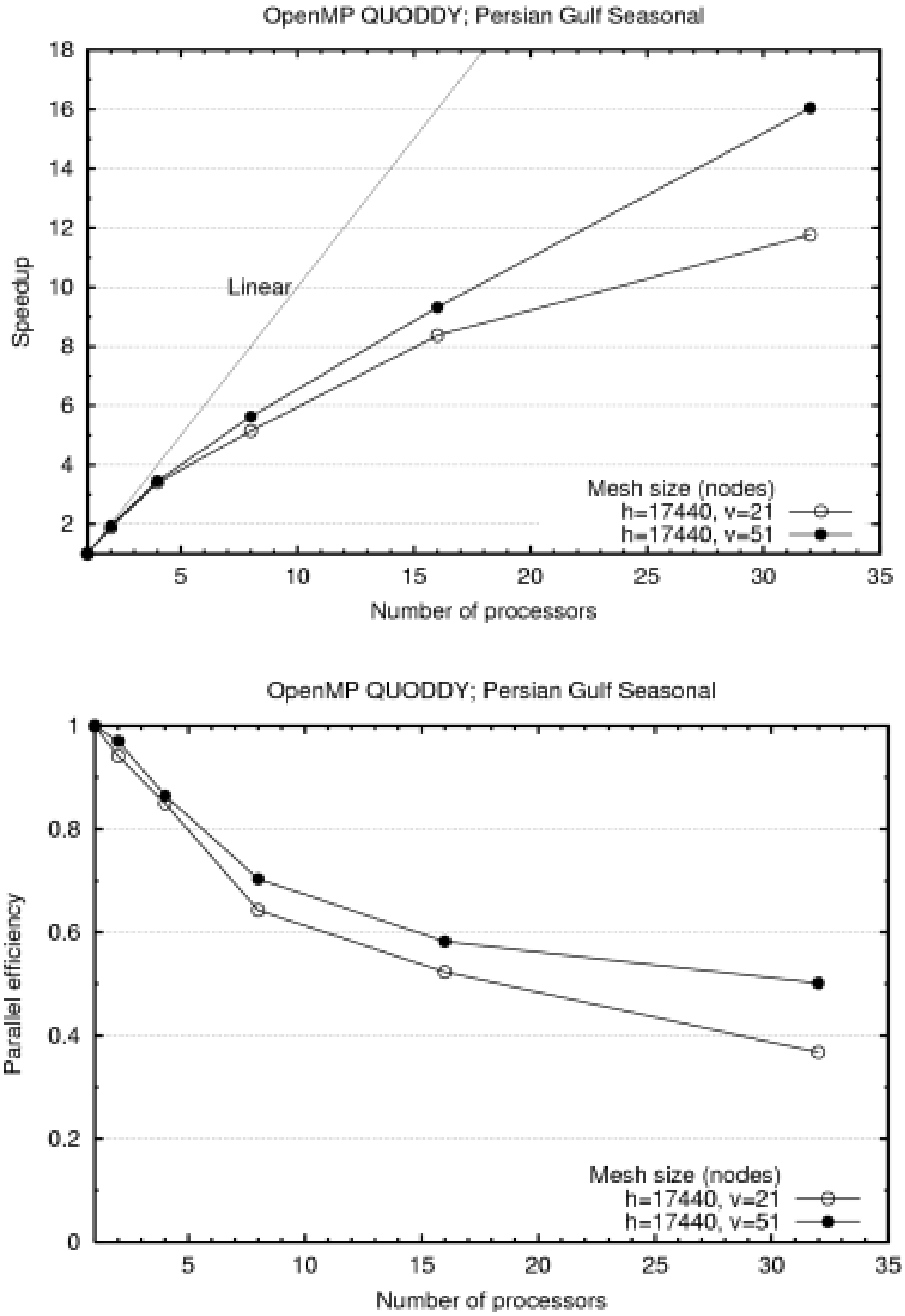

Figure 2. Parallel (a) speed-up and (b) efficiency of the Open-MP implementation in QUODDY for seasonal circulation simulations. Near-linear speed-up up to 8 processors for a 17440 node problem. Efficiency linearly decreases to 60-70% for up to 8 processors with continued slight decreases using more processors. Greater numbers of vertical nodes increase efficiency by 10%. All simulations are performed on the SUN Enterprise 10,000.

IMPACT/APPLICATION

Detailed knowledge and understanding of processes governing shallow water dynamics in the Arabian Gulf and Strait of Hormuz address Naval needs for anticipating variability coastal waters with respect to circulation and water properties over space and time scales relevant to mine-countermine, amphibious, or special operations in this priority area. High horizontal resolution currents assist in the planning of instrumentation and tactics associated with amphibious operations as well as search and rescue efforts. The Arabian Gulf itself is a high priority Naval region.

Advantages of an unstructured grid discretization are evident in the placement of open ocean boundaries, localized resolution refinement, and representation of bathymetric and shoreline complexities. A study of this scope, encompassing the Arabian Gulf, Strait of Hormuz, and Gulf of Oman containing localized mesh refinements of less than 5 km, is unprecedented.

TRANSITIONS

The transitioned operational FE model ADCIRC successfully completed an operational test (OPTEST) at NAVOCEANO for the prediction of tide and wind-forced elevations. Model-data comparisons using NOAA observed water levels at 10 stations along the eastern U. S. formed the basis of the evaluation. Computed elevations have a mean error of 11-12 cm and a phase lag of 11-13 minutes, differences that fall far below the OPTEST criterion.

RELATED PROJECTS

Strong interactions exist with C. E. Naimie and D. R. Lynch (Dartmouth College) regarding model development and application of data assimilation techniques. Collaborations with R. A. Luettich (U. North Carolina) are leading to advancement of the ADCIRC model to include baroclinic physics.

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